Search for neutrino charged current coherent pion production at SciBooNE

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Abstract. SciBooNE is a neutrino experiment measuring neutrino cross sections on carbon in the one GeV region. We have performed a search for charged current coherent pion production from muon neutrinos scattering on carbon, $\nu_\mu {}^{12}\mathrm{C} \rightarrow \mu^- {}^{12}\mathrm{C}\pi^+$. No evidence for coherent pion production is observed. We set 90% confidence level upper limits on the cross section ratio of charged current coherent pion production to the total charged current cross section at 0.67×10^{-2} at a mean neutrino energy of 1.1 GeV and 1.36×10^{-2} at a mean neutrino energy of 2.2 GeV. The kinematic distributions of the final data sample are also presented.

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INTRODUCTION

Neutrino interactions producing single pion form significant backgrounds for neutrino oscillation searches with a few-GeV neutrino beam, and thus understanding these processes is essential. It has been known for years that neutrinos can produce pions by interacting coherently with the nucleons forming the target nucleus. Both charged current (CC) and neutral current (NC) coherent modes are possible, $\nu_\mu A \rightarrow \mu^- A\pi^+$ and $\nu_\mu A \rightarrow \nu_\mu A\pi^0$, where A is a nucleus. The outgoing lepton and pion tend to go in the forward direction in the lab frame, and no nuclear breakup occurs.

There are several experimental measurements in the neutrino energy range between 1 and 100 GeV, including both the charged current and neutral current modes, and using both neutrino and antineutrino probes. These results are well described by the original model of Rein and Sehgal [1]. However, recent results on coherent pion production have induced interest in the neutrino physics community. The non-existence of charged current coherent pion production in a 1.3 GeV wide-band neutrino beam has been reported by K2K [2], while there exist charged current coherent pion production positive results at higher neutrino energies. On the other hand, evidence for neutral current coherent pion production in the similar neutrino energy has been recently reported by MiniBooNE [3].

The SciBooNE experiment [4] is designed to measure the neutrino cross sections on carbon in the one GeV region. In this paper, we report the first measurement of charged current coherent pion production on carbon by neutrinos in the SciBooNE experiment, which was published in ref. [5]. The kinematic distributions of the final data sample are also presented.

THE SCIBOONE EXPERIMENT

The experiment uses the Booster Neutrino Beam (BNB) at Fermilab. The primary proton beam, with kinetic energy 8 GeV, is extracted to strike a 71 cm long, 1 cm diameter beryllium target. Each beam spill consists of 81 bunches of protons, containing typically 4×10^{12} protons in a total spill duration of 1.6 μsec. The target sits at the upstream end of a magnetic focusing horn that is pulsed with approximately 170 kA to focus the mesons, primarily π^+, produced by the $p-$Be interactions. In a 50 m long decay pipe following the horn, π^+ decay and produce neutrinos, before the mesons encounter an absorber. The flux is dominated by muon neutrinos (93% of total), with small contributions from muon antineutrinos (6.4%), and electron neutrinos and antineutrinos (0.6% in total). The flux-averaged mean neutrino energy is 0.7 GeV. When the horn polarity is reversed, π^- are focused and hence a predominantly antineutrino beam is created.

The SciBooNE detector is located 100 m downstream from the neutrino production target. The detector complex consists of three sub-detectors: a fully active fine grained scintillator tracking detector (SciBar), an electromagnetic calorimeter (EC) and a muon range detector (MRD). The SciBar detector consists of 14,336 extruded plastic scintillator

strips, each $1.3 \times 2.5 \times 300$ cm^3. The scintillators are arranged vertically and horizontally to construct a $3 \times 3 \times 1.7$ m^3 volume with a total mass of 15 tons. Each strip is read out by a wavelength-shifting fiber attached to a 64-channel multi-anode PMT. Charge and timing information from each MA-PMT is recorded by custom electronics. The minimum length of a reconstructed track is 8 cm which corresponds to a proton with momentum of 450 MeV/c. The EC is installed downstream of SciBar, and consists of 32 vertical and 32 horizontal modules made of scintillating fibers embedded in lead foils. Each module has dimensions of $4.0 \times 8.2 \times 262$ cm^3, and is read out by two 1" PMTs on both ends. The EC has a thickness of $11X_0$ along the beam direction to measure π^0 emitted from neutrino interactions and the intrinsic ν_e contamination. The energy resolution is $14\%/\sqrt{E[\text{GeV}]}$. The MRD is located downstream of the EC in order to measure the momentum of muons up to 1.2 GeV$/c$ with range. It consists of 12 layers of 2"-thick iron plates sandwiched between layers of 6 mm-thick plastic scintillator planes. The cross sectional area of each plate is 305×274 cm^2. The horizontal and vertical scintillator planes are arranged alternately, and the total number of scintillators is 362.

The experiment took both neutrino and antineutrino data from June 2007 until August 2008. In total, 2.64×10^{20} POT were delivered to the beryllium target during the SciBooNE data run. After beam and detector quality cuts, 2.52×10^{20} POT are usable for physics analyses; 0.99×10^{20} POT for neutrino data and 1.53×10^{20} POT for antineutrino data. Results from the full neutrino data sample are presented in this paper.

EVENT SELECTION

The experimental signature of charged current coherent pion production is the existence of two and only two tracks originating from a common vertex, both consistent with minimum ionizing particles (a muon and a charged pion).

To identify charged current events, we search for tracks in SciBar matching with a track or hits in the MRD. Such a track is defined as a SciBar-MRD matched track. The most energetic SciBar-MRD matched track in any event is considered as the muon candidate. The matching criteria imposes a muon momentum threshold of 350 MeV/c. The neutrino interaction vertex is reconstructed as the upstream edge of the muon candidate. We select events whose vertices are in the SciBar fiducial volume, 2.6 m $\times$ 2.6 m $\times$ 1.55 m, a total mass of 10.6 tons. Finally, event timing is required to be within a 2 μsec beam timing window. The cosmic-ray background contamination in the beam timing window is only 0.5%, estimated using a beam-off timing window. Approximately 30,000 events are selected as our standard charged current sample, which is called the SciBar-MRD matched sample. According to the MC simulation, the selection efficiency and purity of true ν_μ charged current events are 27.9% and 92.8%, respectively. Two subsamples of the SciBar-MRD matched sample are further defined: the MRD stopped sample and the MRD penetrated sample. Events with the muon stopping in the MRD are classified as MRD stopped events. Events with the muon exiting from the downstream end of the MRD are defined as the MRD penetrated sample, in which we can measure only a part of the muon momentum. The average neutrino beam energy for true charged current events in the MRD stopped and MRD penetrated samples is 1.0 GeV and 2.0 GeV, respectively, enabling a measurement of charged current coherent pion production at two different mean neutrino energies.

Once the muon candidate and the neutrino interaction vertex are reconstructed, we search for other tracks originating from the vertex. Most events are reconstructed as either one track or two track events. The two track sample is further divided based on particle identification. The particle identification variable, Muon Confidence Level (MuCL) is related to the probability that a particle is a minimum ionizing particle based on the energy deposition. The probability of misidentification is estimated to be 1.1% for muons and 12% for protons. We first require that the MuCL of the SciBar-MRD matched track is greater than 0.05 to reject events with a proton penetrating into the MRD. Then the second track in the event is classified as a pion-like or a proton-like track with the same MuCL threshold.

In a charged current resonant pion event, $\nu p \to \mu^- p \pi^+$, the proton is often not reconstructed due to its low energy, and such an event is therefore identified as a two track $\mu + \pi$ event. To separate charged current coherent pion events from charged current resonant pion events, additional protons with momentum below the tracking threshold are instead detected by their large energy deposition around the vertex, so-called vertex activity. Events with energy deposition greater than 10 MeV are considered to have activity at the vertex.

Four sub-samples, the one track events, $\mu + p$ events, $\mu + \pi$ events with vertex activity, and $\mu + \pi$ events without vertex activity are used for constraining systematic uncertainties in the simulation. The MC distributions of the square of the four-momentum transfer (Q^2) are fitted to the distributions of the four aforementioned data samples. The reconstructed Q^2 is calculated as

$$Q^2_{\text{rec}} = 2E^{\text{rec}}_\nu (E_\mu - p_\mu \cos\theta_\mu) - m^2_\mu \tag{1}$$

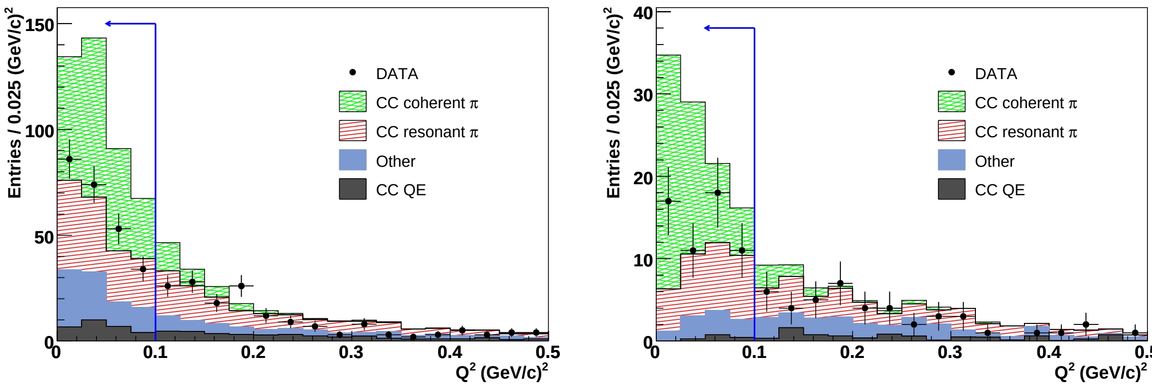

FIGURE 1. Reconstructed Q^2 for the MRD stopped charged current coherent pion sample (left), and the MRD penetrated charged current coherent pion sample (right).

where E_ν^{rec} is the reconstructed neutrino energy calculated by assuming charged current quasi-elastic (CC-QE) kinematics,

$$E_\nu^{\text{rec}} = \frac{1}{2}\frac{(m_p^2 - m_\mu^2) - (m_n - V)^2 + 2E_\mu(m_n - V)}{(m_n - V) - E_\mu + p_\mu \cos\theta_\mu} \tag{2}$$

where m_p and m_n are the mass of proton and neutron, respectively, and V is the nuclear potential, which is set to 27 MeV. The fitting is described in detail in ref. [5].

Charged current coherent pion candidates are extracted from the $\mu+\pi$ events which do not have vertex activity. The sample still contains CC-QE events in which a proton is misidentified as a minimum ionizing track. We reduce this background by using kinematic information in the event. Since the CC-QE interaction is a two-body interaction, one can predict the proton direction from the measured muon momentum and muon angle. For each two-track event, we define an angle called $\Delta\theta_p$ as the angle between the expected proton track and the observed second track directions. Events with $\Delta\theta_p$ larger than 20 degrees are selected. With this selection, 48% of charged current quasi-elastic events in the $\mu+\pi$ sample are rejected, while 91% of charged current coherent pion events pass the cut according to the MC simulation. Further selections are applied in order to separate charged current coherent pion events from charged current resonant pion events which are the dominant backgrounds for this analysis. In the case of charged current coherent pion events, both the muon and pion tracks are directed forward, and therefore events in which the track angle of the pion candidate with respect to the beam direction is less than 90 degrees are selected.

Figure 1 (left) shows reconstructed Q^2 for the $\mu+\pi$ events in the MRD stopped sample after the pion track direction cut. Although a CC-QE interaction is assumed, the Q^2 of charged current coherent pion events is reconstructed with a resolution of 0.016 (GeV/c)^2 and a shift of -0.024 (GeV/c)^2 according to the MC simulation. Finally, events with reconstructed Q^2 less than 0.1 (GeV/c)^2 are selected. In the signal region, 247 charged current coherent pion candidates are observed, while the expected number of background events is 228$\pm$12. The error comes from the errors on the fitting parameters. The selection efficiency for the signal is estimated to be 10.4%. The mean neutrino beam energy for true charged current coherent pion events in the sample is estimated to be 1.1 GeV after accounting for the effects of the selection efficiency.

The same selection is applied to the MRD penetrated sample to extract charged current coherent pion candidates at higher energy. Figure 1 (right) shows reconstructed Q^2 for the MRD penetrated charged current coherent pion sample. In the signal region, 57 charged current coherent pion candidates are observed, while the expected number of background events is 40$\pm$2.2. The selection efficiency for the signal is estimated to be 3.1%. The mean neutrino beam energy for true charged current coherent pion events in the sample is estimated to be 2.2 GeV.

σ(CC coherent π)/σ(CC) CROSS SECTION RATIO

We measure the cross section ratios of charged current coherent pion production to total charged current interaction with two distinct data samples. With the MRD stopped sample, the ratio of the charged current coherent pion

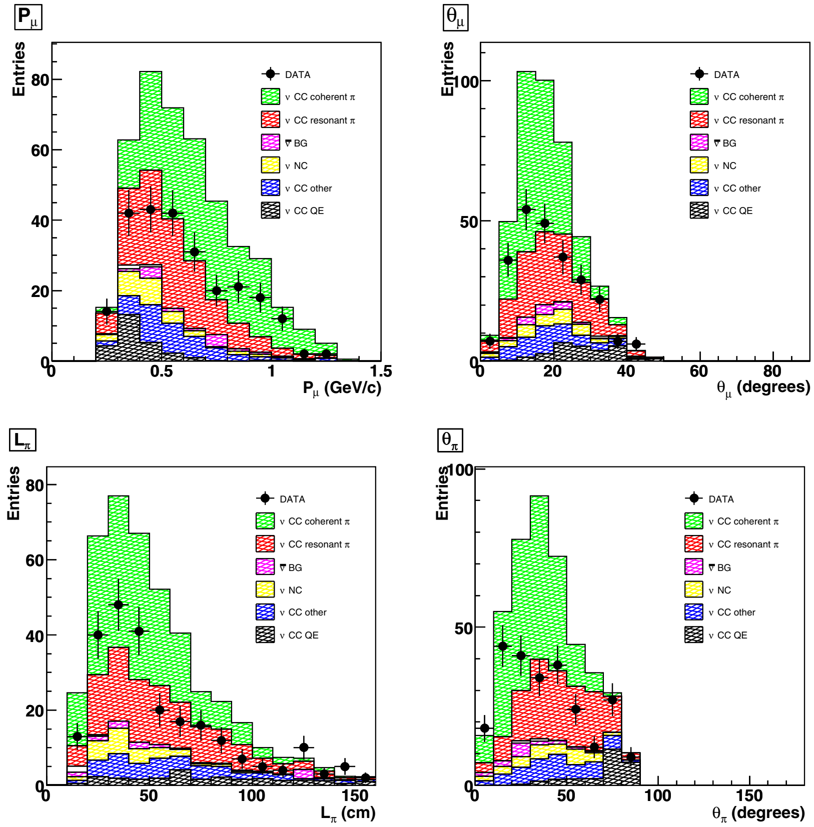

FIGURE 2. Muon momentum, angle, pion track length, and pion angle distributions for the MRD stopped coherent pion sample.

production to total charged current cross sections is measured to be $(0.16 \pm 0.17(stat)^{+0.30}_{-0.27}(sys)) \times 10^{-2}$. The result is consistent with the nonexistence of charged current coherent pion production, and hence we set an upper limit on the cross section ratio by using the likelihood distribution ($\mathscr{L}$) which is convolved with the systematic error. We calculate the 90% confidence level (CL) upper limit (UL) using the relation $\int_0^{UL} \mathscr{L} dx / \int_0^{\infty} \mathscr{L} dx = 0.9$ to be

$$\sigma(\text{CC coherent } \pi)/\sigma(\text{CC}) < 0.67 \times 10^{-2} \tag{3}$$

at a mean neutrino energy of 1.1 GeV.

With the MRD penetrated sample, the cross section ratio is measured to be $(0.68 \pm 0.32(stat)^{+0.39}_{-0.25}(sys)) \times 10^{-2}$. No significant evidence for charged current coherent pion production is observed, and hence we set an upper limit on the cross section ratio at 90% CL:

$$\sigma(\text{CC coherent } \pi)/\sigma(\text{CC}) < 1.36 \times 10^{-2} \tag{4}$$

at a mean neutrino energy of 2.2 GeV.

According to the Rein-Sehgal model [1, 6] implemented in our simulation [7, 8], the cross section ratio of charged current coherent pion production to total charged current interactions is expected to be 2.04×10^{-2}. Our limits correspond to 33% and 67% of the prediction at 1.1 GeV and 2.2 GeV, respectively. Our results are consistent with the K2K result [2]: $\sigma(\text{CC coherent } \pi)/\sigma(\text{CC}) < 0.60 \times 10^{-2}$ at 90% CL measured in a 1.3 GeV wideband neutrino beam.

KINEMATICS DISTRIBUTIONS

Figure 2 shows the distributions of muon momentum, muon angle, pion track length, and pion angle for the MRD stopped coherent pion sample. The distributions of data in Figure 2 are basically in agreement with the background,

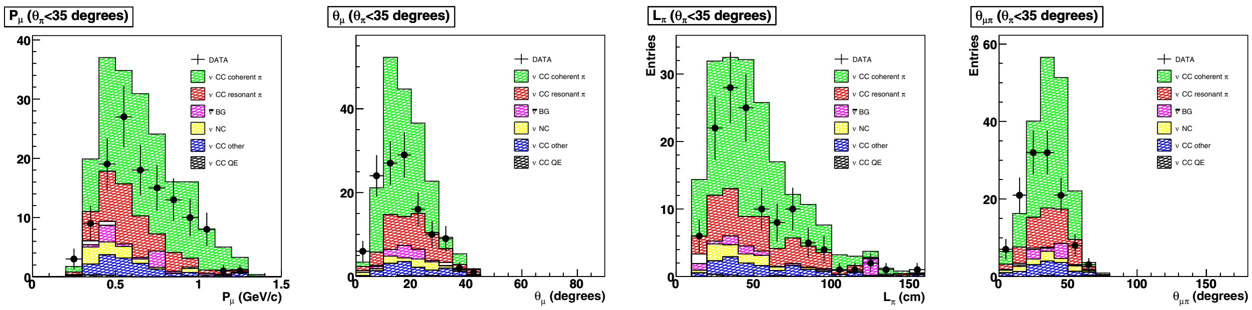

FIGURE 3. Muon momentum, angle, pion track length, and pion angle distributions for the MRD stopped coherent pion events in which pion angle is smaller than 35 degrees.

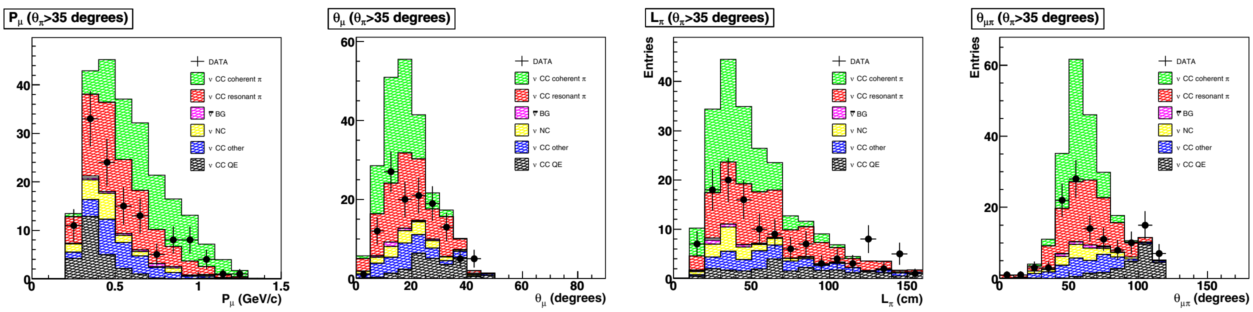

FIGURE 4. Muon momentum, angle, pion track length, and pion angle distributions for the MRD stopped coherent pion events in which pion angle is larger than 35 degrees.

but the data excess seems to cluster at a certain kinematic region: at small pion scattered angle, for example. To investigate the data, the sample is further divided into two sub-samples based on pion scattering angle. Figure 3 and Figure 4 show the kinematic distributions for the MRD stopped coherent pion events with $\theta_\pi < 35$ degrees and $\theta_\pi > 35$ degrees, respectively. The data in the larger pion angle sample is consistent with background prediction while there is an enhancement of the data excess in the smaller pion angle sample. If the data excess is due to charged current coherent pion production, it suggests that pions from charged current coherent pion production tend to go in a more forward direction than the Rein-Sehgal model prediction. The same test has been performed in SciBooNE's antineutrino charged current coherent pion sample [9], and we found a similar enhancement of data excess to that seen in the neutrino data.

Another test has been performed to investigate the data. In the case of charged current coherent pion production, muon and pion are expected to be emitted back-to-back in the *x*-*y* plane because of conservation of momentum. Therefore, the kinematic variable called $\Delta\phi$ is defined as shown in Figure 5. The coherent pion events are expected to distribute around $\Delta\phi = 0$. Figure 6 shows the $\Delta\phi$ distributions for two different pion scattered angle regions in the MRD stopped coherent pion sample. In the large pion angle sample, the data and MC distributions agree well. The charged current quasi-elastic events also distribute around $\Delta\phi = 0$ because of two-body interaction. On the other hand, the data excess is found around $\Delta\phi = 0$ in the small pion angle sample.

These data show that it is important to understand pion kinematics as well as muon kinematics in order to study charged current pion production.

SUMMARY

In summary, we have searched for muon neutrino charged current coherent pion production on carbon in the few-GeV region using the full SciBooNE neutrino data set of 0.99×10^{20} POT. No evidence of charged current coherent pion production is found, and hence we set 90% CL upper limits on the cross section ratio of charged current coherent pion production to total charged current cross sections at 0.67×10^{-2} and 1.36×10^{-2}, at mean neutrino energies of 1.1

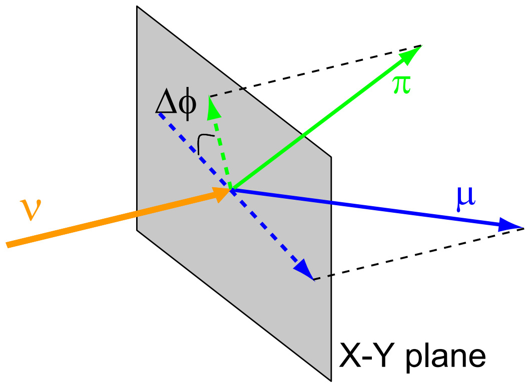

FIGURE 5. Definition of the kinematic variable $\Delta\phi$.

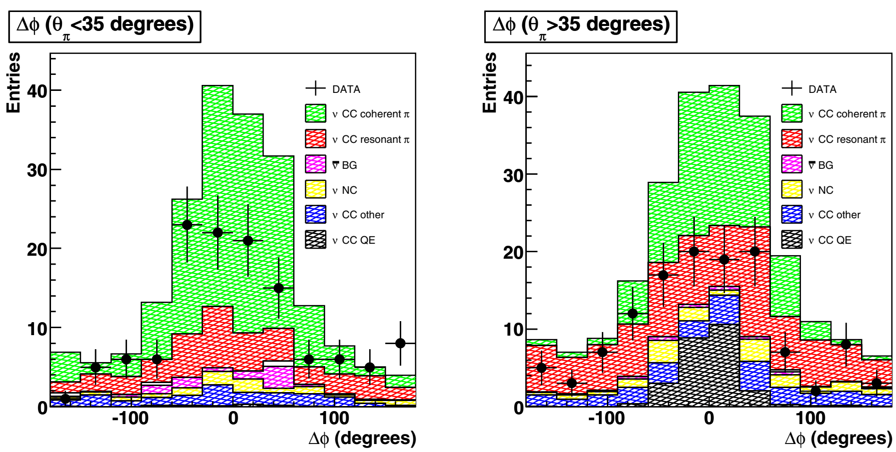

FIGURE 6. $\Delta\phi$ distributions for two different pion scattered angle regions in the MRD stopped coherent pion sample.

GeV and 2.2 GeV, respectively.

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